RXTE / PCA Observations of the Crab Pulsar

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ABSTRACT: We present phase resolved X−ray spectroscopy and the X−ray/radio phase lag for the Crab pulsar obtained through our RXTE monitoring program (now covering nearly 5 years) and from three Target of Opportunity Observations performed within 1.3 to 5.5 days after the large radio glitch recorded on MJD 51740.78 (15 July 2000). The data set is unique among high energy observations for the uniformity and density of sampling and for including the high energy observations soonest after a glitch. Our basic results are summarized as:

− the X−ray pulse leads the radio pulse by 0.011 +/− 0.001 period;
− no significant changes in phase lag or spectral shape are observed immediately following the glitch;
− the pulse phase spectroscopy is consistent with previous analyses.

We also present an update on energy calibation of the PCA relevant for comparing these results with data obtained by other satellites.

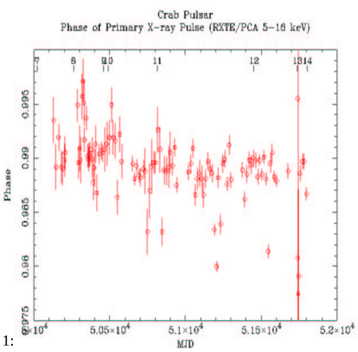

Figure 1:

The absolute (that is, relative to the radio timing) phase of the X−ray primary pulse of the Crab Pulsar has been determined for each of the monitoring observations over the lifetime of the RXTE satellite. (Fig. 1) The barycenter corrections and phasing have been done with the program fasebin, on the basis of the radio timing ephemerides published by the Jodrell Bank radio observatory. A typical phase folded light curve is shown in figure 2; the X−ray phase is determined by fitting a parabola to the 3 highest points in a 100 phase bin light curve. The errors are dominated by the uncertainty in the radio timing ephemerides. The times of all known glitches (7−14) have been marked along the top of the figure 1 (Wong et al., ApJ, in press, astro−ph/0010010). The two large glitches in this period (numbers 8 and 13) occurred while the Crab was in or near the RXTE sun avoidance zone. We have no data within a month of glitch 8; we have data following glitch 13 by just 1.3 days although the nearest pre−glitch observation is two months earlier.

One firm conclusion is that the radio pulse trails the X−ray pulse by 0.011 +/− 0.001 period, or 330 µs. If this is interpretted as a difference in path length, the X−ray pulse originates ~100 km above where the radio pulse emanates from. It is not clear whether the X−ray/radio lag has been slowly increasing over the past 4 years. There is no discernable phase lag across the 2−100 keV band accessible to the RXTE monitoring observations, and the difference in phase between the primary and secondary peaks remains rock−steady at 0.339 periods for all individual observations.

Although most points support a constant lag, there are obvious outliers. In our judgement these points do not represent significant changes in the lag. The four points near MJD 51740 were obtained in the week following glitch 13, at a time when it is difficult to get a good radio timing ephemeris as evidenced by the error bars. We suspect that the other deviant points are also due to errors in the radio timing ephemeris. The Jodrell Bank data are corrected to infinite frequency on the basis of monthly measurements of the Dispersion Measure (DM). If the DM varies strongly on shorter time−scales, this could result in apparent errors in the X−ray phase.

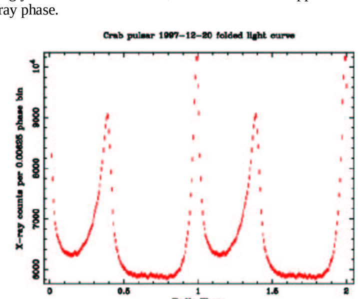

Figure 2.

Variation of Spectral Index with time: We performed power−law fits to the primary (phase interval 0.94 − 1.06) and secondary (0.28 − 0.44) peaks for the entire data set. The results are shown in figure 3; although there is an apparent step coincident with the radio glitch at MJD 51741, we cannot interpret this as evidence for a change in the pulsar spectrum as there was a discontinuity in the PCA performance at just about this time (see the section on Instrument Performance and also figure 7).

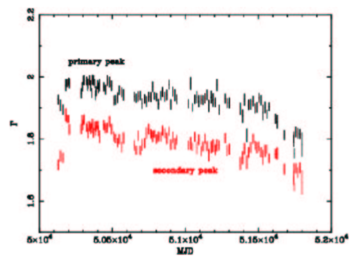

Figure 3. Spectral index of primary and secondary peaks with time. The apparent step near MJD 51700 is an instrumental effect.

Because we cannot separate the data by phase and detector, we further investigated the apparent step by examining the ratio of spectral index fit to the peaks to the spectral index fit to the off pulse interval (phase interval 0.5 − 0.85). The results are shown in figure 4; there is no evidence of a discontinuity associated with the Radio Glitch.

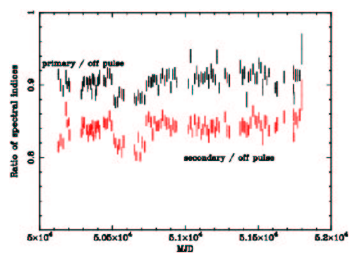

Figure 4: Ratio of spectral indices of pulsar components to nebular component

Data: We have obtained monitoring observations at approximately 2 week intervals over the life of the RXTE mission. Each observation is ~1000 seconds. Phase folded data is obtained by on−board folding at the period predicted and bary−center corrected for the earth's motion (but not the satellite's motion). The folding is carried out for 16 second intervals, and maintains 128 energy channels and ~80 phase bins (minimum 78, maximum 86). This proceedure introduces a small amount of pulse smearing. Data from all detectors and all layers are co−added. Analysis is restricted to energies above 5 keV to avoid an occasional roll−over for phase bins near the primary peak at lower energies. Three ToO observations of ~2000 seconds each were obtained shortly after the glitch (MJD 51740.78) and use an event mode which provides 16 µsec time resolution, 16 energy channels, and maintains PCU id.

All observations include "Standard_2" data which provides 129 channel spectra separately for each layer of each detector, averaged over 16 seconds. Figure 5 summarizes the phase resolved spectra. Each color represents an average over about 20 monitoring observations obtained within one observing season (mid−July to mid−May). The variations are in substantial agreement with previous measurements.

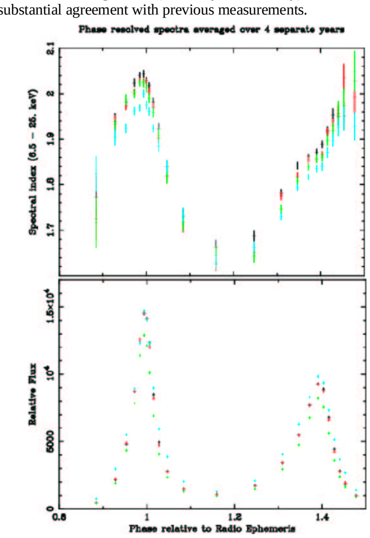

Figure 5.

Instrument Response: The PCA response has changed discontinuously four times (3 high voltage changes at MJD 50163, 50187, and 51259 and the loss of the Propane veto layer in PCU 0 on MJD 51676). Additionally, there are two slow and continuous processes: a slow gain increase (which affects the energy to channel conversion), and a slow increase in the amount of xenon in the propane layer (which affects the quantum efficiency). Figure s 6 and 7 show the time dependence of the spectral index fit to phase averaged Crab data (i.e. Pulsar plus nebula) for individual detectors (fig. 6) and all detectors (fig. 7)